REPORT DOCUMENTATION PAGE AFRL-SR-BL-TR-00-

0527

OSP 66637

Public reporting burden for this collection of information is estimated to average 1 hour per response ... data sources, gathering and maintaining the data needed, and completing and reviewing the collection of informati... aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarter... 115 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, I...

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE 8/22/2000

3. REPORT TYPE AND DATES COVERED Final 3/1/98 - 2/28/99

4. TITLE AND SUBTITLE
Quantum Computing and Optical Memory Using Spectral-Holeburning Techniques

5. FUNDING NUMBERS
F49620-98-1-0286

6. AUTHOR(S)
Dr. Selim Shahriar, Prof. Seth Lloyd, Prof. Shaoul Ezekiel

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
110 Duncan Avenue, Suite B115
Bolling Air Force Base, DC 20332-8050

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
3484/US

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The equipment purchased under this DURIP grant has been used in our project for studying spectral holeburning materials for applications to quantum computing as well as optical memory, using spin coherence excited and controlled by two-photon Raman transitions. The key objective was to demonstrate that NV-Diamond color centers, which has a strong oscillator strength, is suitable for this process. Recently, we have observed efficient Raman transitions, which is manifested as electromagnetically induced transparency, in NV-diamond. Specifically, we have observed near perfect alignment of spin-based quantum bits, and performed single-qubit operations on collections of these qubits. The next step is to realize CNOT operations between spectrally adjacent, distinct quantum bits in this material. The robust nature of Raman excited spin transitions in NV-diamond also establishes it as a viable candidate for ultra-high-density optical memory. Finally, we have also demonstrated recently that the optically excited spin coherence produces ultra-high non-linearity, resulting in slowing the velocity of light pulses down to 45 m/sec. The equipment obtained under this DURIP has been critical to these observations. In the near future, we will expand on this work as we try to realize a many bit quantum computer, as well as a high-temperature optical memory system based on spectral-hole-burning.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

20001023 061

FINAL REPORT

Defense University Research Instrumentation Program

Quantum Computing and Optical Memory Using Spectral-HoleBurning Techniques

By

Dr. Selim Shahriar, Prof. Seth Lloyd and Prof. Shaoul Ezekiel
Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, MA 02139

OSP#: *6663700*
GRANT#: *F49620-98-1-0286*

Abstract

The equipment purchased under this DURIP grant has been used in our project for studying spectral holeburning materials for applications to quantum computing as well as optical memory, using spin coherence excited and controlled by two-photon Raman transitions. The key objective was to demonstrate that NV-Diamond color centers, which has a strong oscillator strength, is suitable for this process. Recently, we have observed efficient Raman transitions, which is manifested as electromagnetically induced transparency, in NV-diamond. Specifically, we have observed near perfect alignment of spin-based quantum bits, and performed single-qubit operations on collections of these qubits. The next step is to realize CNOT operations between spectrally adjacent, distinct quantum bits in this material. The robust nature of Raman excited spin transitions in NV-diamond also establishes it as a viable candidate for ultra-high-density optical memory. Finally, we have also demonstrated recently that the optically excited spin coherence produces ultra-high non-linearity, resulting in slowing the velocity of light pulses down to 45 m/sec. The equipment obtained under this DURIP has been critical to these observations. In the near future, we will expand on this work as we try to realize a many bit quantum computer, as well as a high-temperature optical memory system based on spectral-hole-burning.

Key Words:

Spectral Hole-burning, Quantum Computing, Optical Memory

1.0 INTRODUCTION

We have been pursuing the use of NV color centers in diamond for realizing a many-bit quantum computer, as well as for a high-capacity data storage system. For both of these applications, the first critical step is the creation of coherent spin alignment using two-photon optical (Raman) transitions. Here, we report on our recent observation of this process, and the studies we have conducted to characterize it.

2.0 STATUS OF EXPERIMENTAL WORK CONDUCTED USING THE DURIP EQUIPMENT

Recent developments in the field of quantum information and quantum computing has stimulated an intensive search for coherent physical processes which could be used to manipulate coupled quantum systems in a controlled fashion[1]. In this section, we describe our preliminary results demonstrating Raman excited spin alignment in NV-diamond, and its implication for the coherent generation and manipulation of entangled metastable states of interacting pairs of atoms. Entanglements created this way can in turn be used to realize a quantum computer with hundreds of bits.

We have previously reported in detail on our approach for realizing a quantum computer using a spectral-hole-burning solid[2]. Briefly, in our model a high-finesse optical cavity operating in the strong coupling regime is used to produce, via a two-photon transition, effective dipole-dipole coupling between two color centers that are spectrally adjacent. Recently, we have developed a variant of this approach using direct dipole-dipole interaction, also controlled by a two-photon transition. This model is presented in greater detail in section 7. The experimental parameters of NV-diamond makes it a suitable candidate for realizing either of these approaches for quantum computing.

NV-diamond can be used also for high-temperature hole-burning memories. Optical spectral hole-burning has demonstrated the ability to achieve high-capacity, high-speed data storage[3]. The biggest stumbling block to its widespread application has been the requirement for low temperature operation and the associated costs thereof. To circumvent this problem, we have been investigating the possibility of using Raman excited spin coherences to store and recall optical data. The motivation is that optical Raman excitation allows storage densities and response times characteristic of optical hole-burning memories, but since it is based on long-lived spin coherences, it can maintain these characteristics at much higher operating temperatures. Proof-of-principle experiments have shown the ability to store and recall optical data using Raman excited spin echoes in Pr:YSO. The potential for higher temperature operation, without loss of performance, was also demonstrated in this material. Recently, we have shown that it is possible to observe Raman dark resonances above the spectral hole burning temperature in Pr:YSO. However, to achieve much higher temperature operation, a spectral hole-burning material with an allowed optical transition is required. This is necessary to offset the loss of efficiency of the Raman interaction, due to increasing optical homogeneous width as temperature is increased. NV color centers in diamond is such a medium, and can be used to realize a ultra-high capacity, high temperature as the Raman hole-burning material because it is comparatively well studied[4].

The experimental setup used in the N-V diamond studies is shown in Figure 1. Here, a Raman enhanced non-degenerate four-wave mixing (NDFWM) technique is used to achieve a high signal to noise ratio, in analogy to experimental techniques used previously to study Pr:YSO [5]. In this scheme, coupling (C) and probe (P) field are used to write a grating in the ground state spin coherence via the resonance Raman interaction. This grating is read with a read beam (R) to produce a signal or diffracted beam (D). To further enhance signal to noise, a heterodyne detection scheme is used as shown in Figure 1(b). All dye laser beams are derived from a single dye laser output using acousto-optic frequency shifters. This greatly relaxes dye laser frequency stability requirements since the resonant Raman interaction is insensitive to correlated laser jitter. An additional beam from the argon laser (A) is also directed into the sample to serve as a repump. Without this repump beam, the N-V center would exhibit long-lived spectral hole-burning and no cw signal would be seen after a short time. The Raman transition frequency (~120 MHz) is determined by the spacing between the S=0 and S=-1 ground state spin sublevels. This spacing is controlled by applying a magnetic field of about 1 kGauss along the crystal (111) direction. At this field strength, the S=0 and S=-1 ground sublevels (for N-V centers aligned along (111)) are near an anti-crossing. These conditions are chosen to enhance Raman transition strength by compensating for the small spin-orbit coupling in diamond with a partial mixing the spin sublevels[4].

The observed NDFWM signal is shown in Figure 2 as a function of Raman detuning. The amplitude of this signal is directly proportional to the degree of coherent spin alignment induced in the NV color centers. For convenience, the Raman detuning is adjusted by tuning the spacing between the S=0 and S=-1 sublevels using the applied magnetic field. As shown, the Raman linewidth is about 20 MHz, which is comparable to the 15 MHz inhomogeneous width of the ground state spin transition. This width is significantly smaller than the homogeneous width (>>25 MHz) of the optical transition and laser jitter (~100 MHz), and is taken as evidence of the Raman process. The asymmetry in the lineshape is due to interference with the (much broader) NDFWM signal at the anti-crossing. To eliminate this interference and to improve quality of the NDFWM signal, scanning of probe beam frequency is required. This was achieved by introducing electro-mechanical galvos. Compensating of angular displacement of coupling, probe, and reading beams, galvos allow scanning frequency of all beams. To further expand capability of the experimental setup, RF drivers for AOMs were configured to scan difference frequency between coupling and probe beam. A representative NDFWM signal obtained with modified setup is shown in Figure 3 as a function of frequency difference between coupling and probe beam. The value of the magnetic field was chosen about 1 kGauss and maintained constant.

Large optical matrix elements are required to maximize the number of gate operations per decoherence time. To evaluate matrix elements of our system, we investigated NDFWM diffraction amplitude as a function of laser intensity. The results are shown in Figure 4 for different laser intensities of coupling and probe beams. Intensity of the read beam was 25 W/cm^2, and intensity of the repump beam was around 10 W/cm^2. Saturation intensities were found to be 5 W/cm^2 and 3 W/cm^2 for coupling and probe transition respectively. Relatively high values of saturation intensities might be explained high optical density of this particular sample. Using obtained values of optical matrix elements, we can expect 100-1000 logic gate operations per spin decoherence time.

It is interesting to note that laser intensity has a great influence not only on amplitude of the NDFWM signal, but also on symmetry of lineshape. Figure ~~5~~ 6 illustrates observed this dramatic change in lineshape.

Trying to optimize experimental conditions for observation of NDFWM signal, we studied NDFWM signal lineshape as a function of applied magnetic field. The experimental results are show in Figure 7. Sharp reduction in amplitude of the observed NDFWM signal far from central frequency most likely can be explained by limited bandwidth of the AOM used to scan the frequency of the probe beam. Further investigation of the obtained dependencies with proper renormalization of the signal is planed for the future.

Finally, Raman induced transparency of the probe field (P) has also been observed. Applying coupling laser power about 13 W/cm^2 , absorption suppression of the probe beam (1.3 W/cm^2) was evaluated to be about 4% (that corresponds change in transmission to be about 2.5%). Experimental traces are presented in Figure 8.

As a first step in investigation of spin echo in NV-diamond, we studied optical pumping effect on population of ground state. Regular NMR signal was detected at 430 MHz with applied magnetic field of 920 Gauss. RF power was modulated by square wave with frequency 50 Hz. Considering long lifetime of the metastable ground state, fall time of the observed pulses was strongly depended on efficiency of optical pumping. Experimental decay curve revealed two components: one weak component had constant fall time of about 5 ms, and the second stronger component had much shorter fall time, heavily depended on laser intensity. Therefore, weak component was attributed to unknown background signal, and the strong component was attributed to studied optical pumping effect. Experimental decay curves and corresponding fitting curves are shown in Figure 9.

To summarize, preliminary analysis of the NV-diamond shows a good potential of this material for experimental realization of solid state quantum computing based on dipole-dipole coupling. We have estimated that existing sample can provide as many as 900 coupled qubits per laser spot for quantum computing in spectrally selective solids. We have observed and stuided Raman excited spin alignments. We have also analyzed the effects of laser power and magnetic field on Raman enhanced non-degenerate four-wave mixing signal. We have determined the optical matrix elements to be strong enough to allow 100-1000 logic gates operation per spin decoherence time.

References

1. C. Williams and S. Clearwater, Exploration in Quantum Computing (Springer-Verlag, New York, 1998).
2. M.S. Shahriar, J. Bowers, S. Lloyd, and P.R. Hemmer, "Solid State Quantum Computing Using Spectral Hole Burning," quant-ph/0007074
3. H. Lin, T. Wang, and T. W. Mossberg, "Demonstration of 8-Gbit/in.2 areal storage density based on swept-carrier frequency-selective optical memory," *Optics Letters* **20**, pp. 1658-1660 (1995); X. A. Shen, E. Chiang, and R. Kachru, "Time-domain holographic image storage," *Optics Letters* **19**, pp. 1246-1248 (1994)
4. X.F. He, N.B. Manson, P.T.H. Fisk, "Paramagnetic resonance of photoexcited N-V defects in diamond. I. Level anticrossing in the ^{3}A ground state," *Physical Review B* **47**, 8809 (1993); A. Lenef, S. W. Brown, D. A. Redman, S. C. Rand, J. Shigley and E. Fritsch, "Electronic structure of the N-*V* center in diamond: Experiments," Physical Review B 53, 13427-13440 (1996).
5. B. S. Ham, M. S. Shahriar, M. K. Kim and P. R. Hemmer, "Frequency-selective time-domain optical data storage by electromagnetically induced transparency in a rare-earth-doped solid," *Optics Letters* **22**, pp. 1849-1851 (1997).
6. P.R. Hemmer, A. Turukhin, J. Mosser, and M.S. Shahriar, *quant-ph/0007114.*

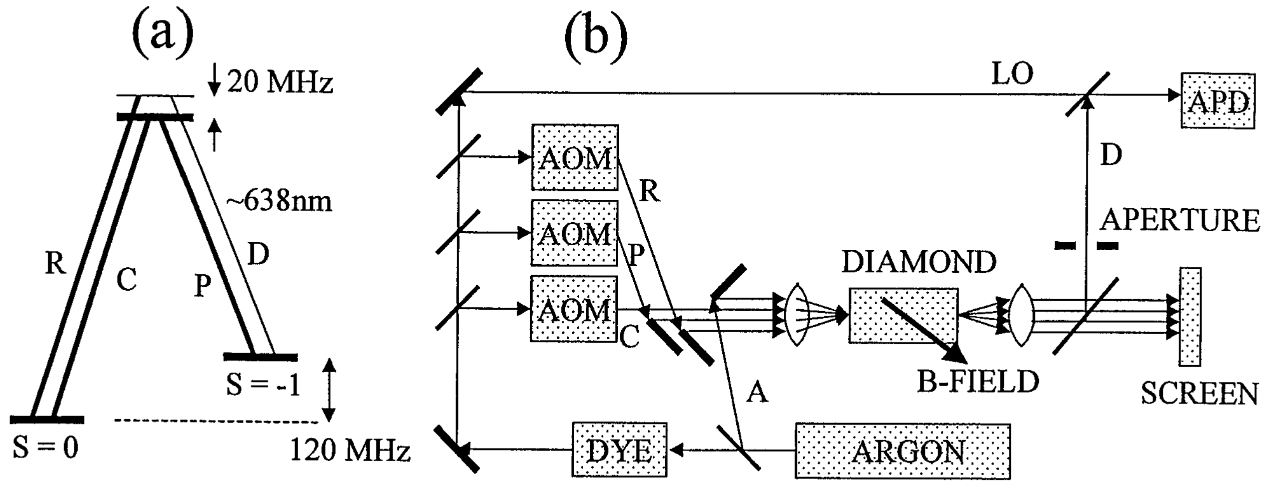

Figure 1. Experimental setup for observation of Raman excited spin coherences in N-V diamond. (a) Level diagram near anti-crossing. (b) Optical table setup.

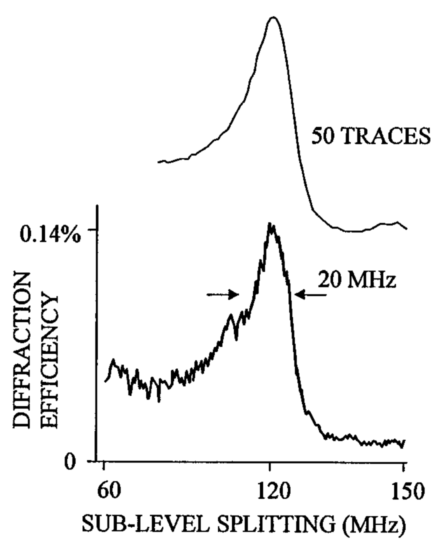

Figure 2. Raman enhanced non-degenerate four-wave mixing signal vs. magnetic field induced splitting of S=0,-1 states.

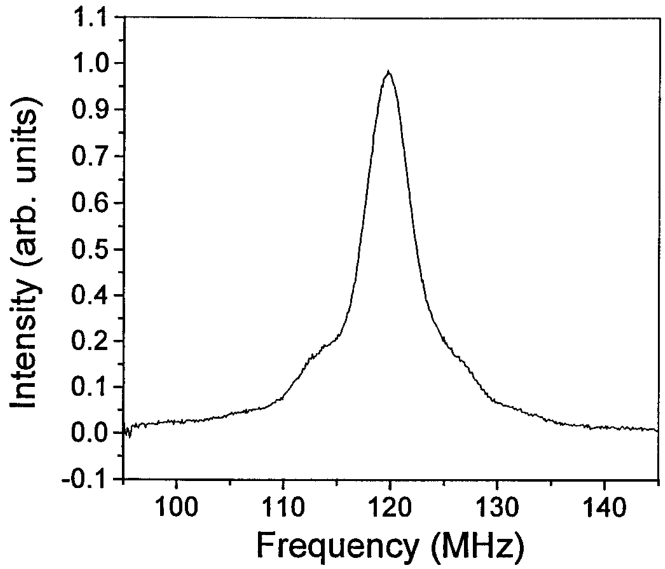

Figure 3. Raman enhanced non-degenerate four-wave mixing signal vs. frequency difference between coupling and probe beam.

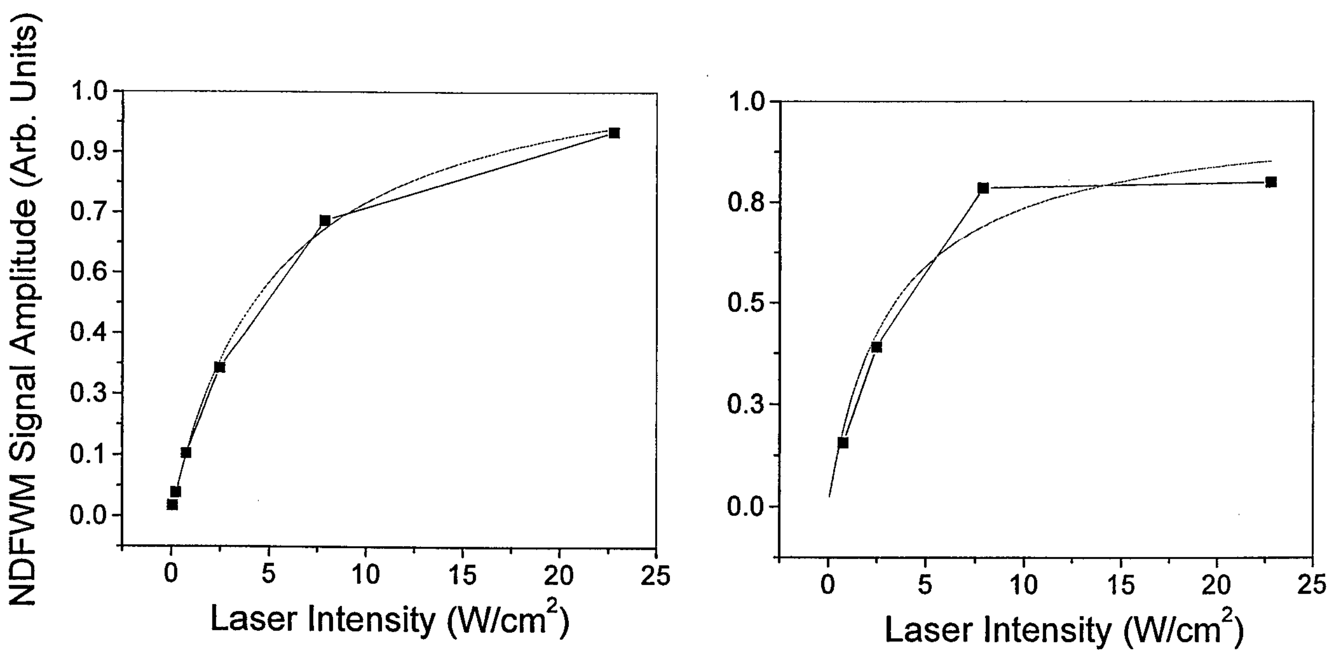

Figure 4. Amplitude of Raman enhanced non-degenerate four-wave mixing signal vs. laser intensity of coupling (left chart) and probe (righ chart) beams.

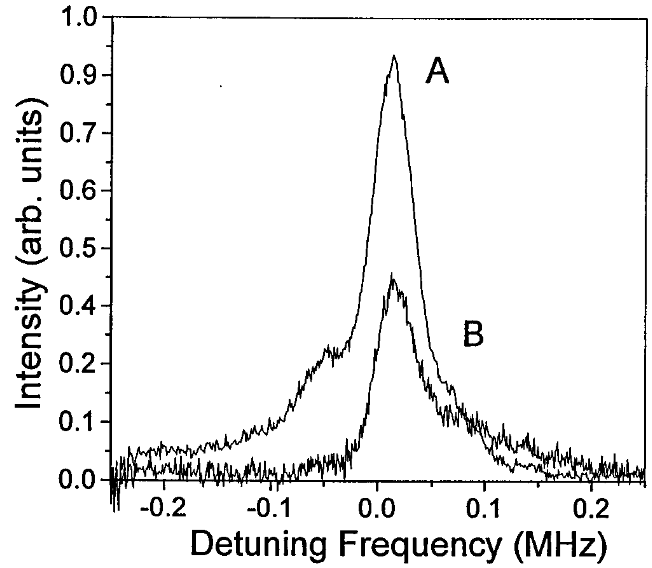

Figure 6. Observed raman enhanced non-degenerate four-wave mixing signal lineshape with applied full laser power (trace A) and 1/3 of full laser power (trace B).

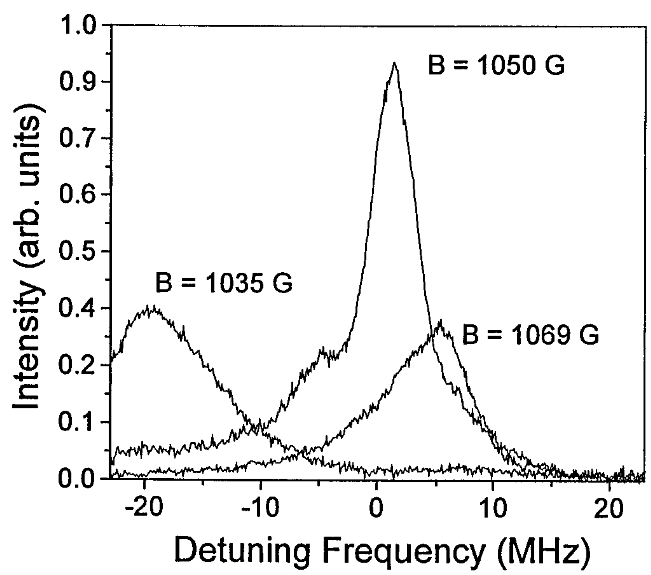

Figure 7. Raman enhanced non-degenerate four-wave mixing signal vs. magnetic field strength.

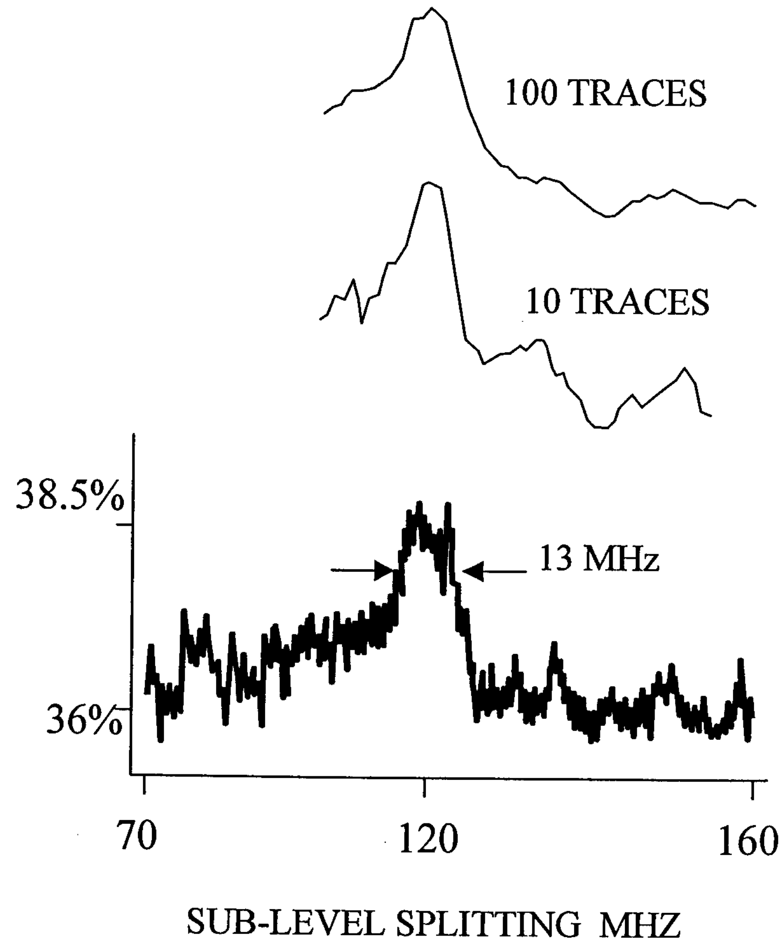

Figure 8. Absorption suppression in NV-diamond. Observed change in probe beam transmission is shown.

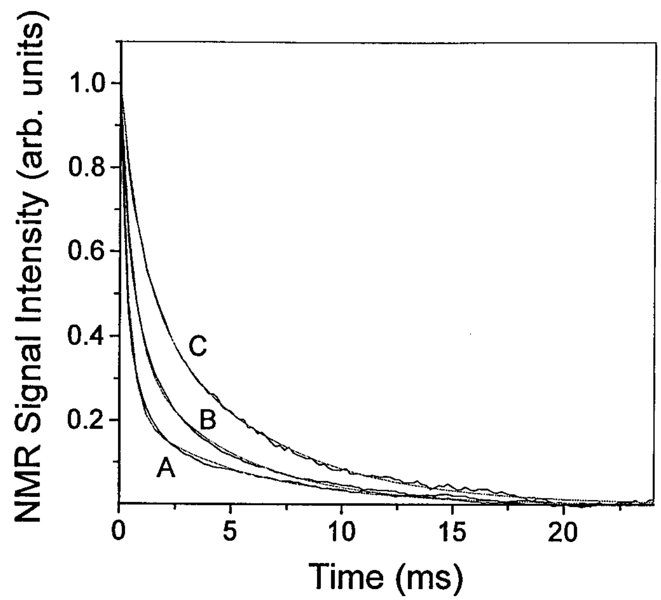

Figure 9. Ground state optical pumping after RF-pulse in NV-diamond. Optical pumping times of 0.40 ms, 0.58 ms, and 0.94 ms were found for laser powers of 96 mW/cm^2, 48 mW/cm^2, and 24 mW/cm

List of equipment purchases on Grant#: F49620-98-1-0286
Quantum computing and Optical Memory Using Spectral-Hole Burning

Manufacturer	Item	Amount
Beta Lamb Instruments	2 Ch. 200 MHz Digital Scope	$3,357.50
Sony	CCD TRV99 Ultra-sensitive Video Camera Camera with Mount	$1,274.98
Coherent Laser	Innova 308 Argon Ion Laserr and Actively Stabilized, Scanning Single Frequency Ring Dye Laser	$118,890.96
Varian	Vacuum Pump w/ Water Cooled Diffusion Pump	$2,190.00
Electronic Measurements	0-20 vdc & 0-500 amps output / 208 vac 3 phase input / digital meters	$5,240.00
Gateway 2000	Computer System	$1,371.00
Isomet	2 Acousto-Optic Modultors	$1,438.38
Mini-Circuits	Broadband AMPL / BNC Female connectors	$537.07
Nor-Cal Products	2 CF 6-way Cross Model No. 6C-400V	$2,342.70
Stanford Research Systems	Low Noise Preamplifier	$2,046.70
Stanford Research Systems	Function Gemerator	$2,137.75
Stanford Research Systems	Digital Delay Generator	$3,896.00
Sigma-Aldrich	Gow-Mac Gas Leak Detector	$1,295.00